

# Precision X-ray measurements on kaonic atoms at LNF

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## **Abstract.**

After the successfully performed DEAR experiment at DAΦNE - resulting in the most precise data on the hadronic shift and width in kaonic hydrogen up-to-now - the next step will be the measurement at the percent level using new X-ray detectors. These detectors (silicon drift detectors) are developed within the SIDDHARTA project. The asynchronous background will be suppressed using the time correlation between the kaon and the X-ray by 2-3 orders of magnitude. These measurements will lead to precise values of the isospin-dependent antikaon-nucleon scattering lengths, thus opening a new insight in the low-energy kaon nucleon interaction.

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## INTRODUCTION

In general exotic atoms are extremely valuable test systems for research in many fields of physics, like the study of fundamental interactions (e.g. strong interaction in hadronic atoms) and fundamental symmetries (e.g. CPT tests with antiprotonic helium and anti-hydrogen).

The experimental studies of simple hadronic atoms as kaonic hydrogen - in which the electron is substituted by a negatively charged kaon - provide the straightforward investigation of the strong antikaon-nucleon interaction at lowest energy. Whereas the principal interaction in kaonic hydrogen atoms is electromagnetic the effect of the strong interaction leads to the experimentally observable shift  $\varepsilon_{1s}$  from the electromagnetic value and to a width  $\Gamma_{1s}$  due to the reduced life time of the ground state. The electromagnetic value of the  $K_\alpha$  transition can be calculated by solving the Klein-Gordon equation taking into account various corrections like vacuum polarization etc. [1]. The physical values of the observables  $\varepsilon_{1s}$  and  $\Gamma_{1s}$  can be measured to a high degree of precision by X-ray spectroscopy of the transitions to the ground state (K transitions) in kaonic hydrogen and deuterium.

In kaonic hydrogen the  $\Lambda(1405)$  sub-threshold resonance - a 4 star object in the listings of the Particle Data Group [2] - leads to the repulsive-type kaon-proton interaction at threshold [3]. The nature of  $\Lambda(1405)$  is still in discussion. According to theory [4]  $\Lambda(1405)$  can be identified as a  $K^-p$  bound state. Following this theory the existence

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of deeply bound kaonic clusters [5] is anticipated. The search for these kaonic nuclear clusters is currently conducted in experimental studies at GSI and LNF [6, 7] and in the future at LNF and J-PARC (Japan) [8, 9].

The extraction of the isospin-dependent scattering lengths requires the knowledge of  $\varepsilon_{1s}$  and  $\Gamma_{1s}$  of kaonic hydrogen as well as deuterium. No experimental data on the strong interaction in kaonic deuterium atoms are available up to now. The investigation of kaonic deuterium will be more challenging also due to the anticipated low yield of the X-ray transitions to the ground state.

An ambitious experimental program devoted to kaonic atoms was started by the DEAR (DAΦNE Exotic Atom Research) collaboration [10]. DAΦNE - the electron-positron collider at Laboratori Nazionali di Frascati (LNF) turned out to be the ideal machine for this kind of research. It delivers nearly mono-energetic  $K^-$  mesons ( $E_K \sim 16$  MeV) from the  $\Phi$  decay with a branching ratio of  $\sim 50\%$ . The DAΦNE performance in providing low-energy kaons to be stopped in gas targets is unique and by far superior compared to accelerators used in former experiments which produced large hadronic background. Another advantage was ensured by X-ray detectors (charge-coupled-devices, CCDs) with significantly higher energy resolution ( $\sim$  factor 2 better than Si(Li) detectors). However, the drawback of CCDs is the limitation in the background suppression. Since CCDs have no timing capability only background leading to pixel clusters (background from gamma rays or charged particles) can be suppressed by analyzing the hit pattern.

The DEAR experiment was successfully performed. The X-ray spectrum of kaonic nitrogen was measured and even more important DEAR obtained the most precise values of the strong interaction shift and width in kaonic hydrogen up to now.

The continuation of the exotic atom program at LNF will employ large area silicon drift detectors (SDDs) which are providing timing capability as well as high energy resolution like CCDs. These detectors are already produced by the SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by Timing Application) Collaboration. A completely new setup with a large array of these SDDs was designed and is being near completion.

## **EXPERIMENTS AND RESULTS**

### **Kaonic atoms at DAΦNE**

Experimental X-ray studies of kaonic nitrogen and finally of kaonic hydrogen were performed by the DEAR Collaboration. This line of experiments verified that DAΦNE represents the ideal site for kaonic atom experiments with stopped kaons. Cryogenic gas targets with a hydrogen gas density (3% of liquid density) were employed to provide sufficient kaon stop efficiency and low losses due to Stark effect leading to kaon absorption from higher  $s$  states. The X-ray detection was performed by an array of 16 CCDs (type CCD-55). The energy calibration was done in-beam using the fluorescence lines from the structure materials of the experiment. Extremely important for the kaonic hydrogen measurement was the treatment of the large soft X-ray background. Background data from measurements without electron-positron collisions and from the

kaonic nitrogen measurements were used.

## **Kaonic hydrogen - Results**

For the first time kaonic nitrogen X-ray spectra of the kaonic transitions 5-4, 6-5 and 7-6 (i.e. transitions not influenced by strong interaction) were measured [11]. These data are important for the kaonic cascade theory and also for feasibility studies for future precision experiments on the charged kaon mass.

The DEAR experiment verified the repulsive type of the kaon-proton interaction found by the KEK experiment [12] but obtained smaller values for  $\epsilon_{1s}$  and  $\Gamma_{1s}$  with higher precision [13]:  $\epsilon_{1s} = -193 \pm 37(stat.) \pm 6(syst.)$  eV and  $\Gamma_{1s} = 249 \pm 111(stat.) \pm 30(syst.)$  eV. These results stimulated new theoretical studies on kaonic hydrogen [14, 15, 16, 17].

## **THE SIDDHARTA EXPERIMENT**

### **X-ray detector development**

In spite of the fact that in DEAR the most precise values of  $\epsilon_{1s}$  and  $\Gamma_{1s}$  were extracted the goal of precision measurements at the percent level calls for a new experiment. The precision of the DEAR results was mainly limited by the high soft X-ray background leading to a signal-to-noise ratio of  $\sim 1:70$ . The background consists of a synchronous component related to the produced kaons (hadronic background) and asynchronous background coming from electromagnetic showers produced by beam electrons lost due to Touschek effect or residual gas interaction. Using a new type of X-ray detectors (SDD) the limitation by the high asynchronous background will be overcome.

The new SDD detectors provide very good energy resolution (comparable with CCDs) but also timing capability (see table 1). The charged kaon pair ( $K^+ + K^-$ ) emitted in the  $\Phi$  decay can be used as well suited trigger since the kaons are nearly monoenergetic and emitted back-to-back. The application of a triple coincidence between the kaon pair and the X-ray will suppress efficiently the asynchronous background component by about 2-3 orders of magnitude.

An array of 12 subunits (total active area  $216 \text{ cm}^2$ ) will surround the cryogenic gas target. This target-detector system is in development by the SIDDHARTA Collaboration [20, 21, 22] and will be setup at DAΦNE in 2007.

### **Setup development**

The SIDDHARTA setup was guided by the successful design of the DEAR setup. The construction phase started in the second half of 2006 and will be finished in spring 2007. A first prototype of the cryogenic target cell was developed and built. The light

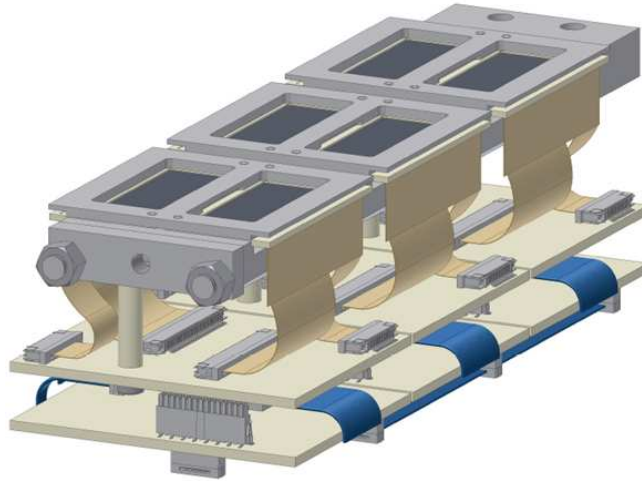
**TABLE 1.** Comparison between the X-ray detectors CCDs and SDDs.

X-ray detector	CCD	SDD
Type	CCD55-30	SIDDHARTA
Active area [mm <sup>2</sup> ]	724	100
Number of detectors in array	16	216
Total active area [cm <sup>2</sup> ]	116	216
Energy resolution [eV]	~150	~140
Time resolution FWHM [ns]	no	~400

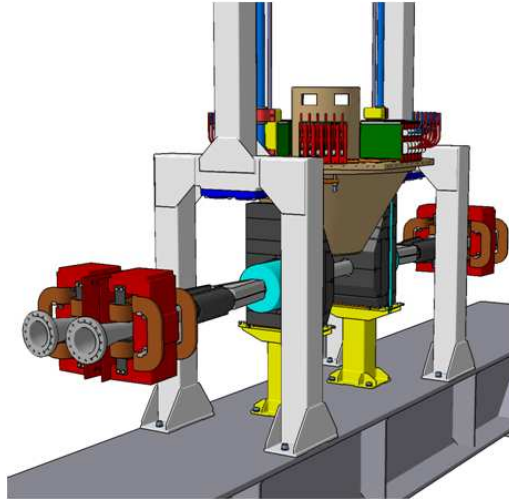
**TABLE 2.** The properties of kaonic hydrogen and kaonic deuterium atoms are shown. The values  $\epsilon_{1s}$  and  $\Gamma_{1s}$  of kaonic deuterium according to recent theoretical studies are given.

Kaonic atom	KH	KD
$K_{\alpha}$ e.m. value [eV]	6480	7810
$\epsilon_{1s}$ [eV]	~ 200	~ 325 [18]
$\Gamma_{1s}$ [eV]	~ 250	~ 630 [18]
X-ray yield ( $K_{\alpha}$ ) [%]	1-3	~ 0.2

weight cell is made only from selected materials (pure aluminium and Kapton) and was successfully tested at a temperature of 25 K. The material used for this setup, especially for the target cell, the SDD mounting and the structure material in the vicinity of the SDD chips were carefully analyzed by PIXE (Proton Induced X-ray Emission) at VERA [23]. The element content of the materials in use was detected with a sensitivity for Fe



**FIGURE 1.** A SDD subunit assembled with 6 SDD chips (active area in total 18 cm<sup>2</sup>). The setup of the X-ray detection system will consist of 12 subunits.



**FIGURE 2.** Schematic view of the SIDDHARTA setup at the intersection.

impurities in the ppm range. The iron content of the mechanical components was always less than 50 ppm, as required by the experiment. Also the ceramic frame of the SDD chip was analyzed and the ceramic material with the lowest iron content was selected. The installation of the whole experimental setup at DAΦNE is planned for mid of 2007.

### **Monte Carlo simulations for kaonic hydrogen and deuterium**

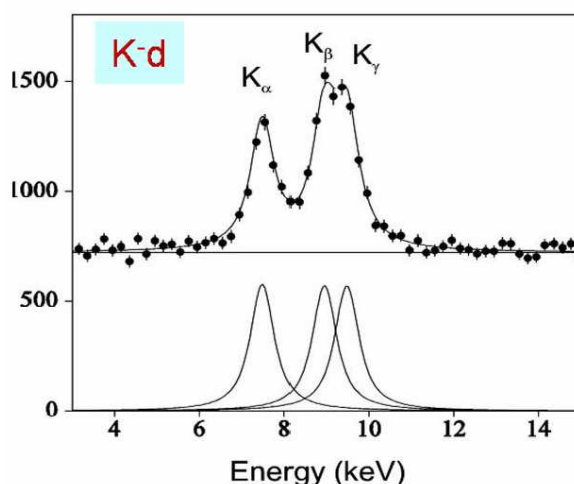
Monte Carlo simulations for the SIDDHARTA setup show that a precision at the percent level can be anticipated for  $\epsilon_{1s}$  and  $\Gamma_{1s}$  of kaonic hydrogen. More challenging might be the measurement of the X-ray spectrum of kaonic deuterium because of the experimentally unknown but as an order of magnitude smaller anticipated  $K_{\alpha}$  X-ray yield (see tab.2). Furthermore, theoretical predictions on the strong interaction width differ [19].

Assuming an average luminosity of  $10^{32} \text{ cm}^{-2}\text{s}^{-1}$  in a beam time of  $\sim 60$  days  $> 5 \cdot 10^4$  kaonic hydrogen  $K_{\alpha}$  events can be collected - therefore sufficient to fulfill the goal of a percent level measurement. In the kaonic deuterium case a Monte Carlo simulation (see fig.3) shows that measurement becomes feasible. In the SIDDHARTA experiment more than 5000 kaonic deuterium  $K_{\alpha}$  events can be collected in 60 days.

The Monte Carlo simulations show that even with an assumed width of 1200 eV the values of  $\epsilon_{1s}$  and  $\Gamma_{1s}$  10 % can be measured with  $< 10\%$  uncertainty.

### **OUTLOOK**

First test measurements with the new X-ray detection system and the new setup are foreseen to take place in 2007.



**FIGURE 3.** Monte Carlo simulation of the kaonic deuterium X-ray spectrum assuming the values: shift = -325 eV, width = 630 eV, X-ray yield = 0.2%. In this case the shift and the width can be determined with a precision of <6% and <8%, respectively.

At the highest priority measurements on kaonic hydrogen and kaonic deuterium will be performed - these data are highly requested [24].

With the shift and width data of kaonic hydrogen and deuterium the isospin-dependent scattering lengths can be extracted. New experimental information about the kaon-proton interaction at threshold and the elusive  $\Lambda(1405)$  resonance - important for the research on deeply bound kaonic systems - will be provided. Moreover, kaonic helium ( $^4\text{He}$  and  $^3\text{He}$ ) will be studied in the framework of SIDDHARTA.

## ACKNOWLEDGMENTS

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